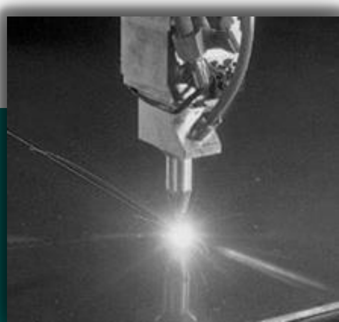
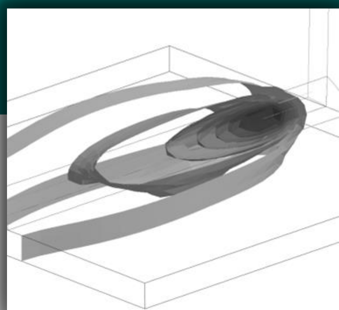
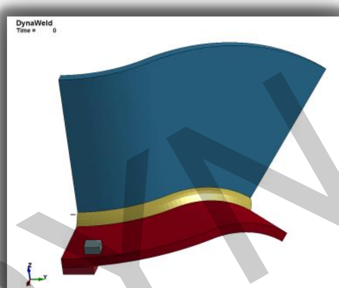






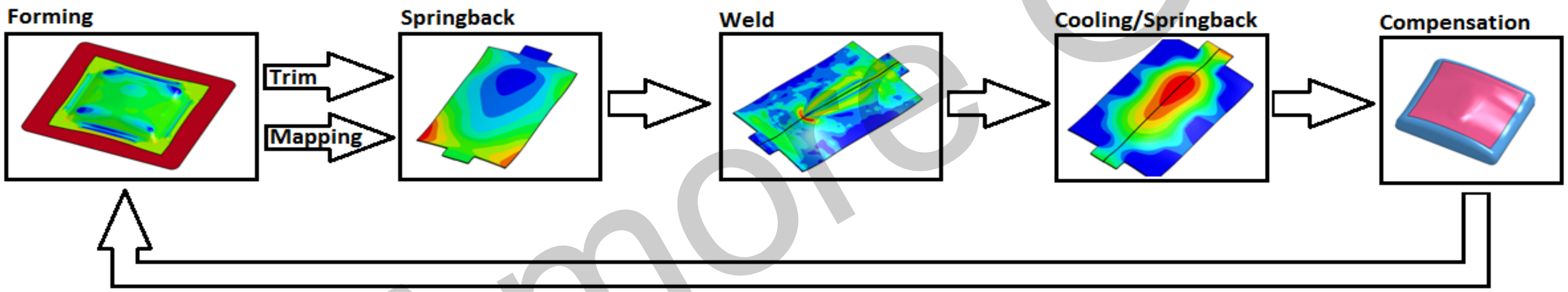
Solver- und Materialmodellentwicklungen bei DYNAmore für die Simulation von Schweißen und Wärmebehandlung

Thomas Klöppel

DYNAmore GmbH

Simulation of the manufacturing process chain

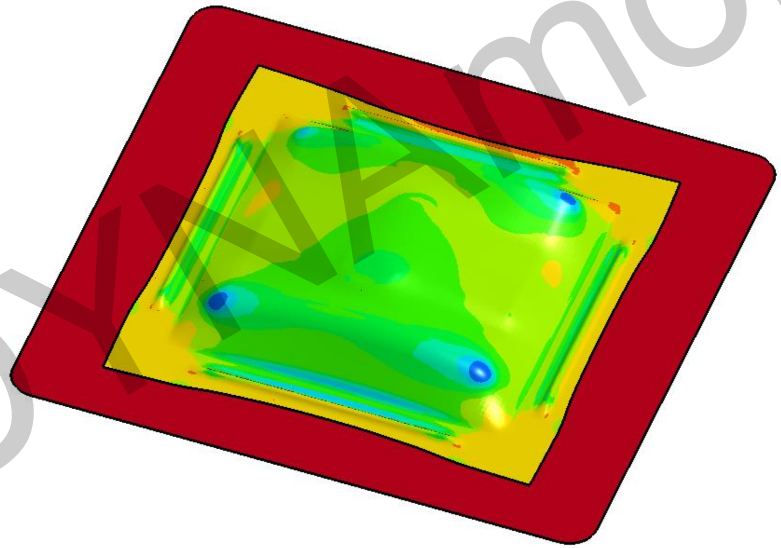
- For modern processes and materials, the mechanical properties of the finished part highly depend on the fabrication chain
- Tooling has to be compensated for springback and shape distortions which occur in the fabrication chain

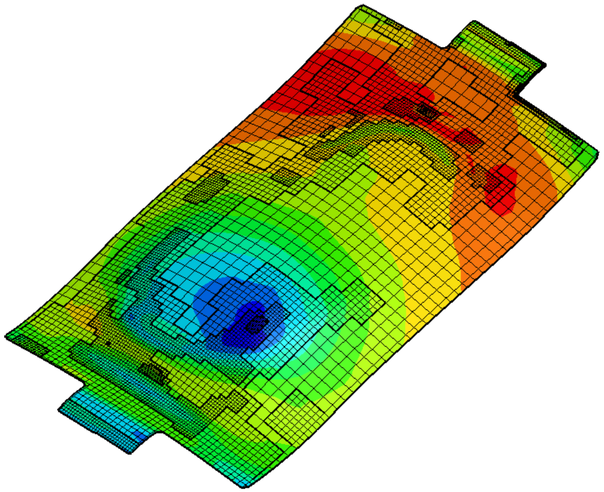


- Numerical simulations of the complete process chain necessary to predict finished geometry and properties
- The individual stages pose very different requirements on the numerical solver

Forming simulation in LS-DYNA

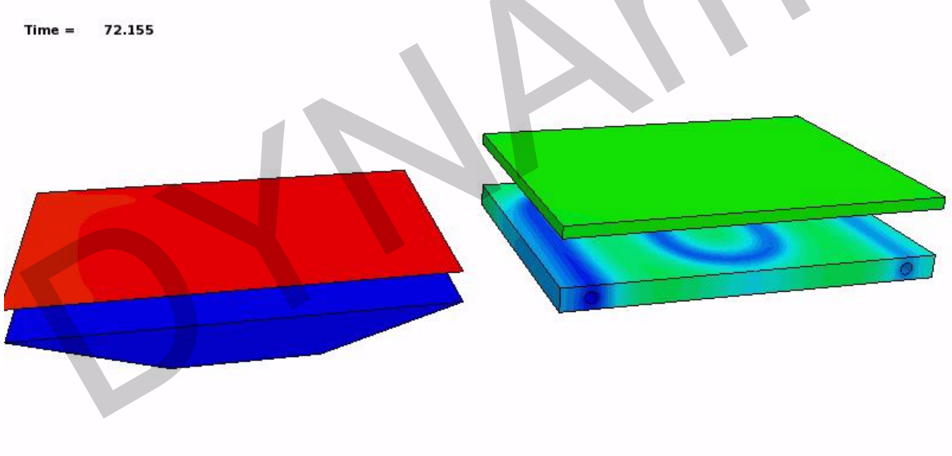
- Different state-of-the-art shell element formulations
- A variety of anisotropic, (visco-)elasto-plastic material formulations
- Forming contacts
- h-adaptivity for improved accuracy and reasonable simulation times
- Implicit (e.g. gravity) and explicit (e.g. closing, drawing) operations
- Trimming functionality

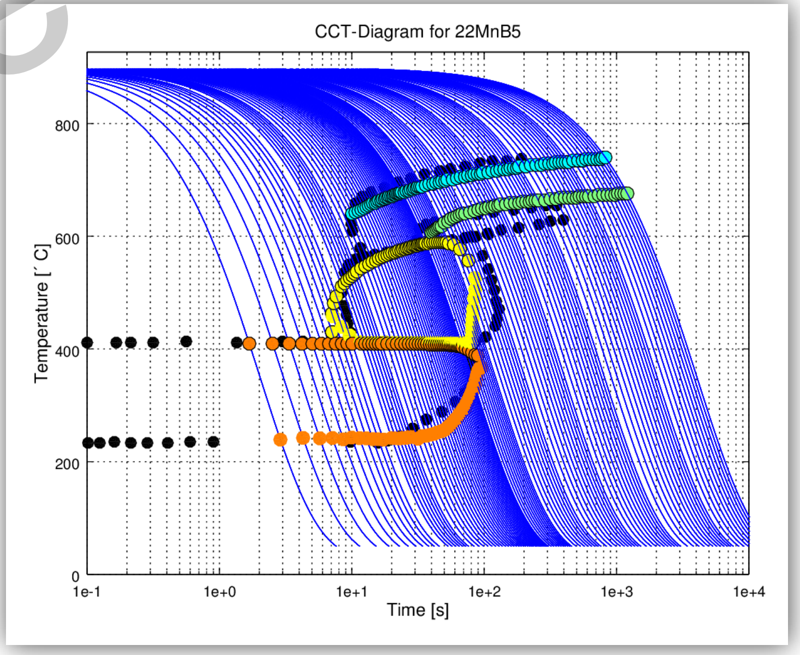




Hot stamping simulation

- Coupled thermo-mechanical simulations
- Thermal contact mechanics
- Among others, tailored material formulation MAT_UHS_STEEL
  - Phase transition of austenite into ferrite, pearlite, bainite and martensite for cooling
  - Thermo-visco-elasto-plastic properties can be defined for individual phases
  - Transformation induced plasticity algorithm
  - Hardness computation
- Tool cooling analysis is also possible





Welding simulations – requirements

- Realistic description for the heat source applied to the weld seam

- Weld seams are usually discretised with solid elements in the pre-processing
  - Before the weld torch has reached the material, filler should not influence the outcome
    - Very low mechanical stiffness
    - Very low heat conduction
  - When affected by the heat, material should respond as the surrounding material

- Due to the very high temperature, annealing effects have to be considered

- Material should be able to account for the microstructure of the alloy
  - Phase changes in heating and cooling
  - Transformation induced strains

Agenda

- Modeling Heat Sources in LS-DYNA
  - The Goldak heat source
  - Heat sources with arbitrary shape and prescribed trajectories
- Suitable Material formulations in LS-DYNA
  - *MAT_CWM (*MAT_270)
  - *MAT_THERMAL_CWM (*MAT_T07)
  - *MAT_UHS_STEEL (*MAT_244)
- Summary and Outlook

Goldak Double Ellipsoid heat source

- double ellipsoidal power density distribution proposed in [Goldak2005]

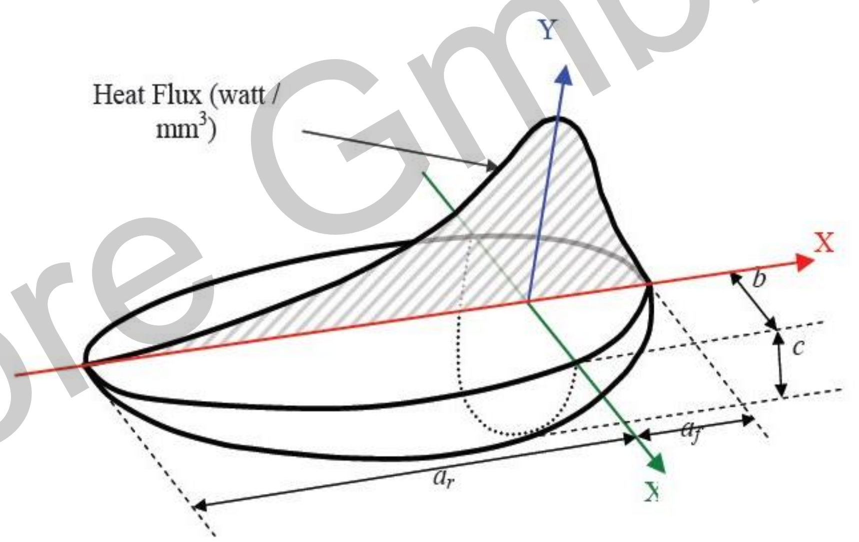
$$q = \frac{6\sqrt{3}FQ}{\pi\sqrt{\pi}abc}\exp\left(\frac{-3x^2}{a^2}\right)\exp\left(\frac{-3y^2}{b^2}\right)\exp\left(\frac{-3z^2}{c^2}\right)$$

q = weld source power density

(x, y, z) = coordinates of point p in weld material

$$F = \begin{cases} F_f \text{ if point } p \text{ is in front of beam} \\ F_r \text{ if point } p \text{ is behind beam} \end{cases}$$

$$c = \begin{cases} c_f \text{ if point } p \text{ is in front of beam} \\ c_r \text{ if point } p \text{ is behind beam} \end{cases}$$

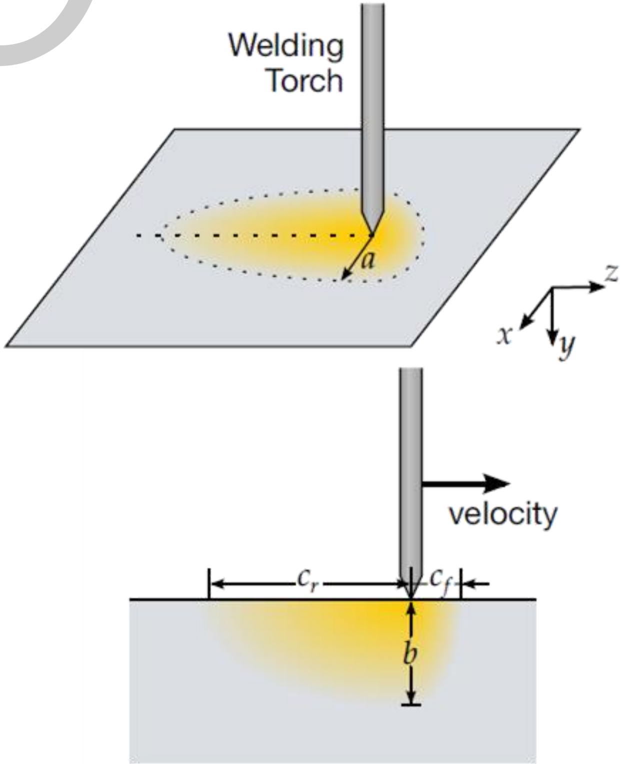


- Most widely used for industrial applications
- Can be defined in LS-DYNA using keyword *BOUNDARY_THERMAL_WELD

*BOUNDARY_THERMAL_WELD

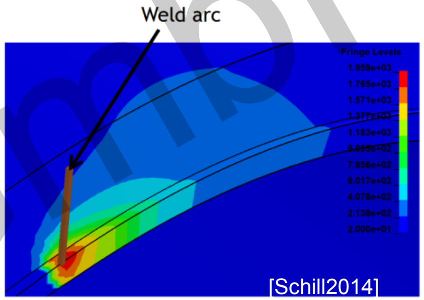
	1	2	3	4	5	6	7	8
Card 1	PID	PTYP	NID	NFLAG	X0	Y0	Z0	N2ID
Card 2	a	b	cf	cr	LCID	Q	Ff	Fr
Opt.	Tx	Ty	Tz					

- NID: Node ID giving the location of weld source
- NFLAG: Flag controlling motion of source
  EQ.1: source moves with node
  EQ.0: fixed in space
- N2ID: Second node ID for weld beam direction
  GT.0: beam is aimed from N2ID to NID
  EQ.-1: beam aiming direction is (Tx, Ty, Tz)



Movement of the heat source 1

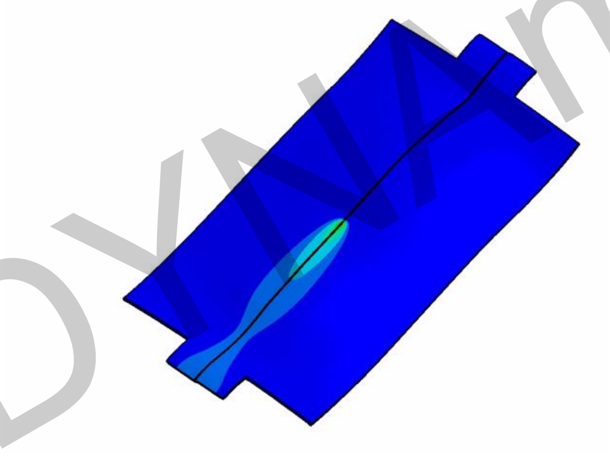
- Beam motion (e.g. *BOUNDARY_PRESCRIBED_MOTION_RIGID) allows defining the translation and rotation of the heat source

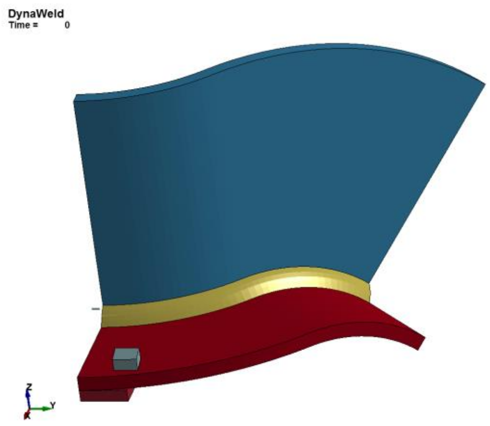


Temperature

- For previously deformed or curved structures, the description of the heat source is NOT straight-forward

- Movement of the part has to be compensated for





Movement of the heat source 2

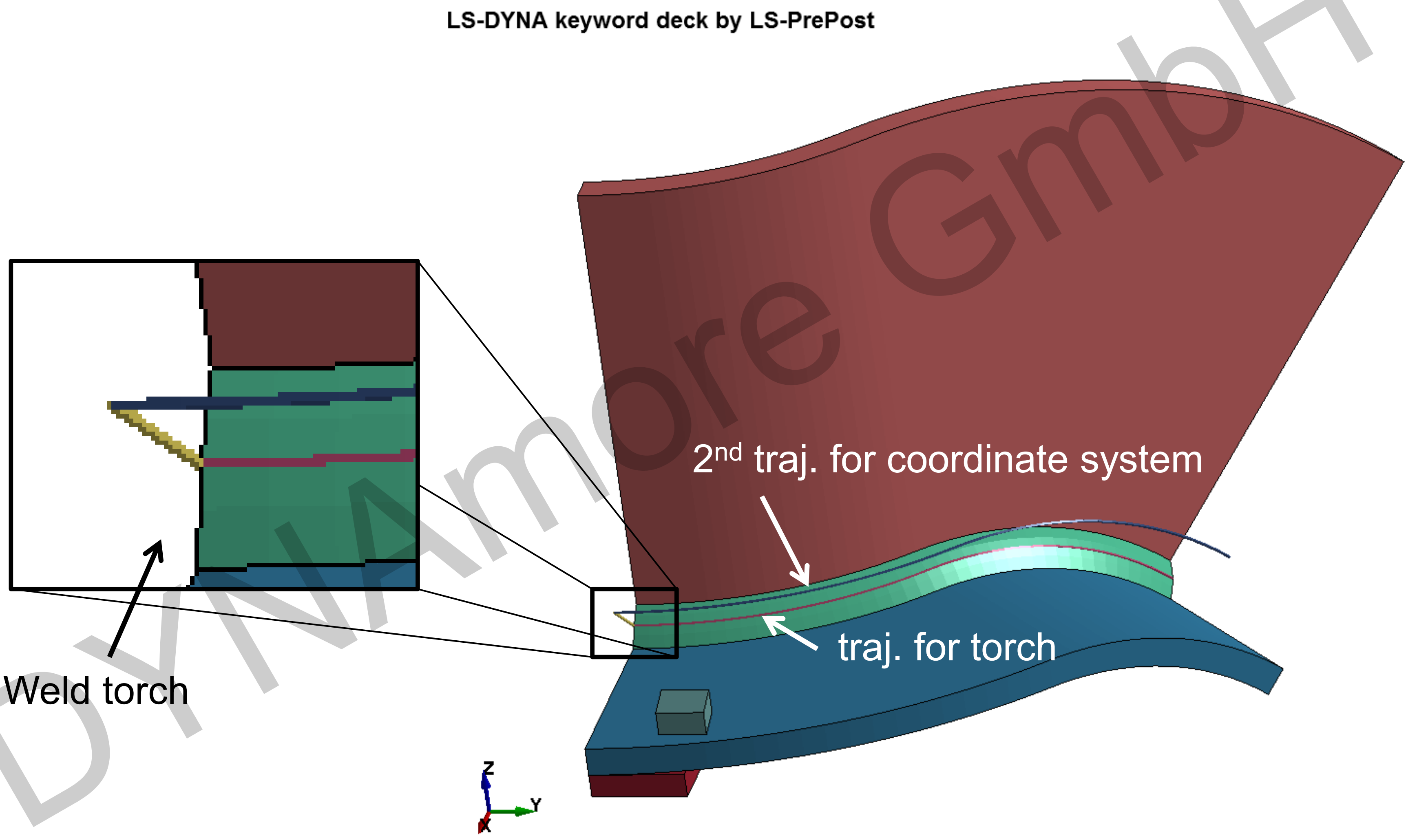
- Useful keyword: *CONTACT_GUIDED_CABLE

	1	2	3	4	5	6	7	8
Card 1	NSID	PID	CMULT	WBLCID	CBLCID	TBLCID		

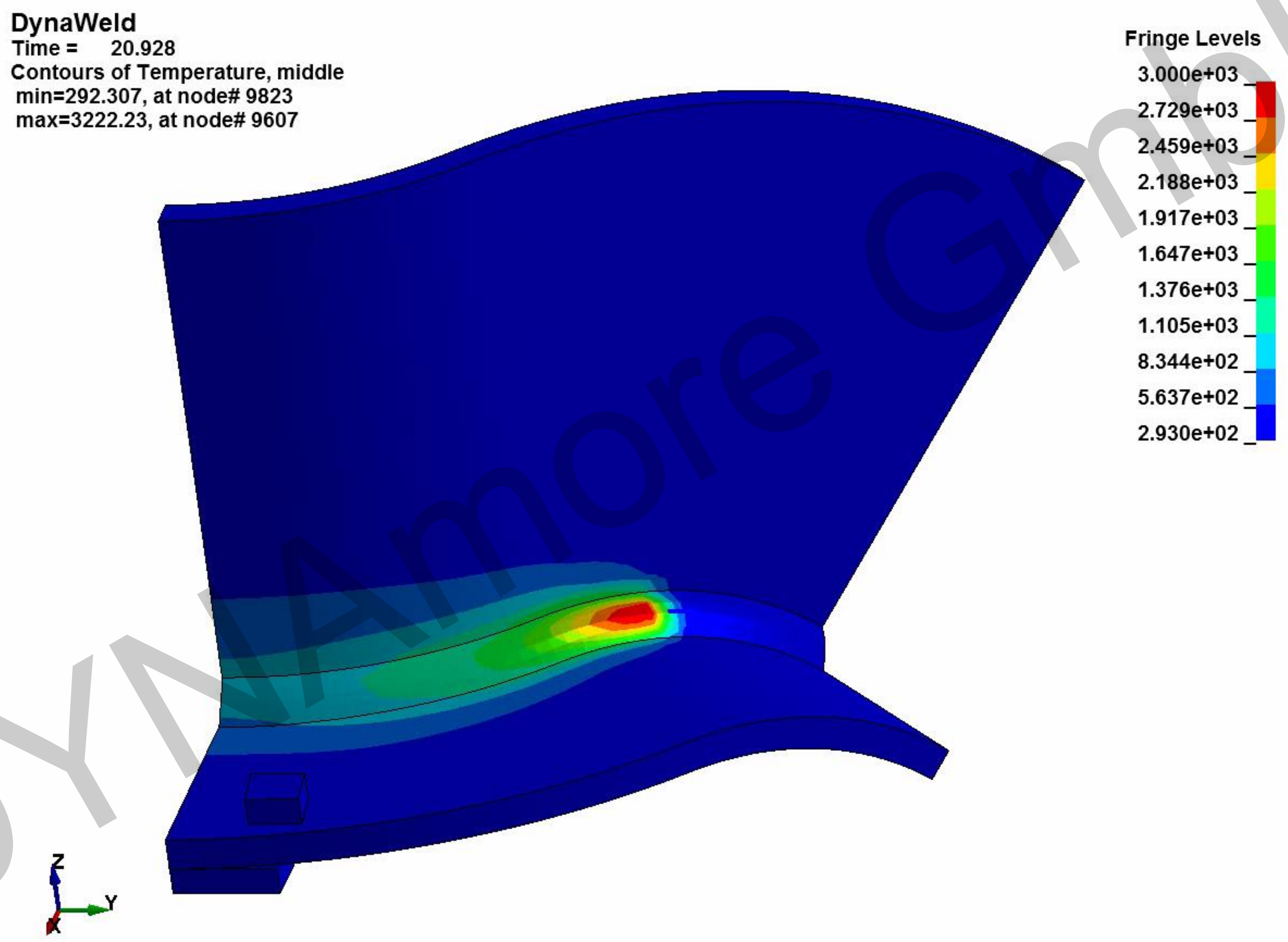
  - It forces beams in PID onto the trajectory defined by nodes in NSID

- Possible solution
  - Select a trajectory on the weld seam
  - Define contact between this trajectory and a beam B1 (N1 and N2)
  - Define a second trajectory and a beam B2 (N3 and N4) following it in a prescribed manner
  - Welding torch aiming directions from N3 to N1 (*BOUNDARY_THERMAL_WELD)
  - Define local coordinate system N1,N2,N3
  - Use *BOUNDARY_PRESCRIBED_MOTION_RIGID_LOCAL to move heat source

Movement of the heat source - example



Movement of the heat source - example



Heat sources with arbitrary shape

- In some cases the standard Goldak heat source is not suitable
- *LOAD_HEAT_GENERATION_*OPTION* might be useful

	1	2	3	4	5	6	7	8
Card 1	SID	LCID	CMULT	WBLCID	CBLCID	TBLCID		

  - LCID accepts a function id, that returns `heat(t,x,y,z)`

- *DEFINE_FUNCTION
  - Define arithmetic expressions involving a combination of independent variables and other functions
  - Function name must be unique (`heat` for heat generation)
  - Can be referenced in other functions
  - C-type or FORTRAN-style code is possible

*LOAD_HEAT_GENERATION_*OPTION**

- Example: Define moving (along x) spherical heat source

```
*LOAD_HEAT_GENERATION_SET
      1001      1001        1.0           0          0          0
*DEFINE_FUNCTION
      1001
float heat(float time, float x, float y, float z)
{    float xl,rl,f;
     xl=x-xt(time);
     if (xl**2+y**2+z**2>=1) f=0;
      else f= sqrt(1- xl**2+y**2+z**2);
      return f;}
*DEFINE_FUNCTION
      4001
float xt(float time)
{   float f = 10*time;
    return f;}
```

x distance from center (reference)

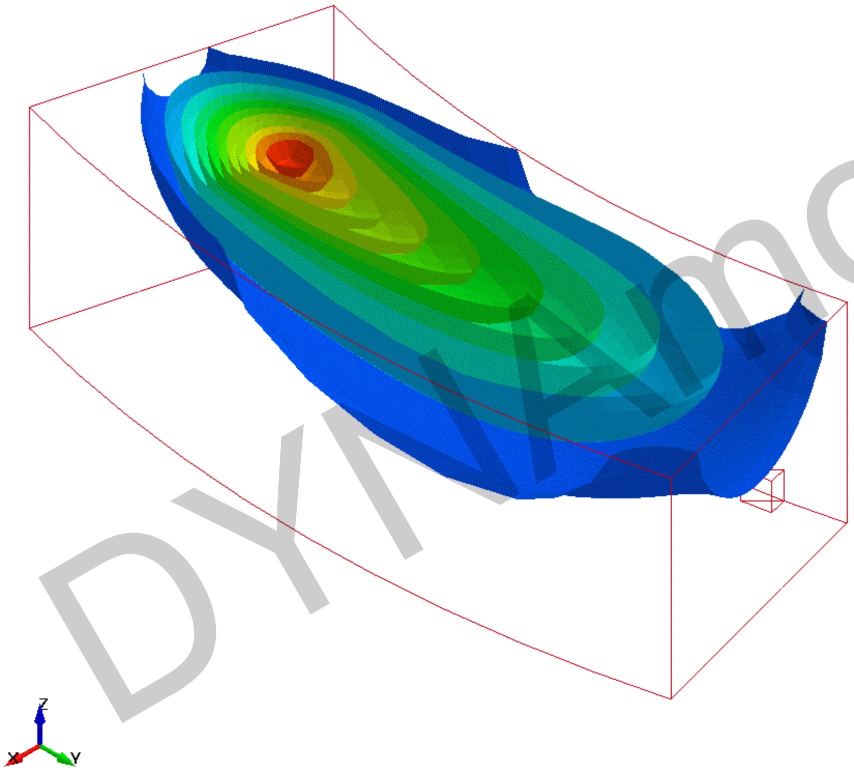
No heat generation outside sphere

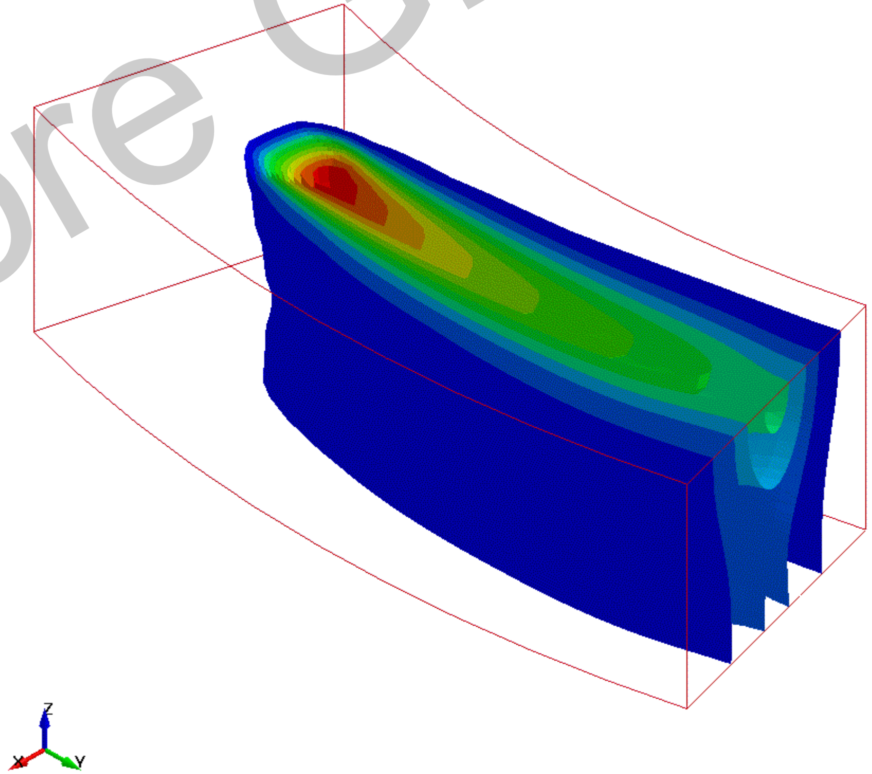
Spherical heat source

Motion along x-axis with v=10

*LOAD_HEAT_GENERATION_*OPTION**

- Example:
  Temperature fields for a Goldak and a double cone-shaped heat source





Define heat source for 2D

- Can be modeled with flux boundary condition

- With *BOUNDARY_FLUX_SEGMENT_SET arbitrarily shaped sources can be defined

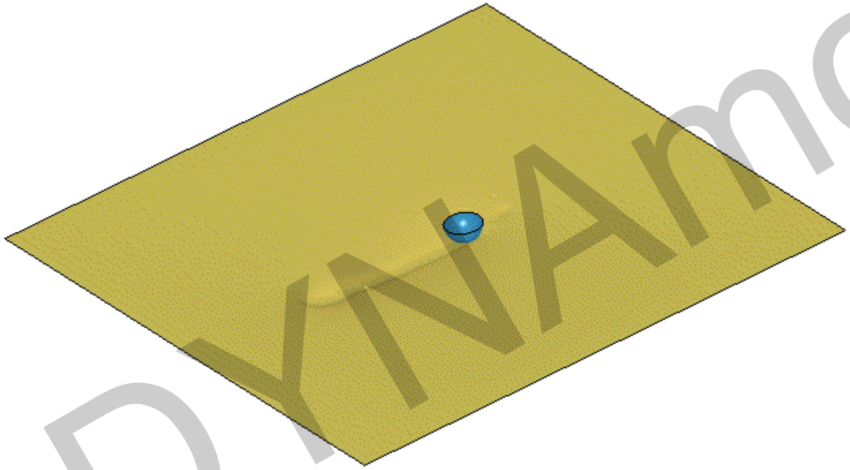
	1	2	3	4	5	6	7	8
Card 1	SID							
Card 2	LCID	MLC1	MLC2	MLC3	MLC4	LOC	NHISV	
Card x	HISV1	HISV2	HISV3	HISV4	HISV5	HISV6	HISV7	HISV8

  - Accepts function ID in `LCID`, declaration
    `float flux(float x,float y,float z,float vx,float vy,float vz,float tinf,float time)`

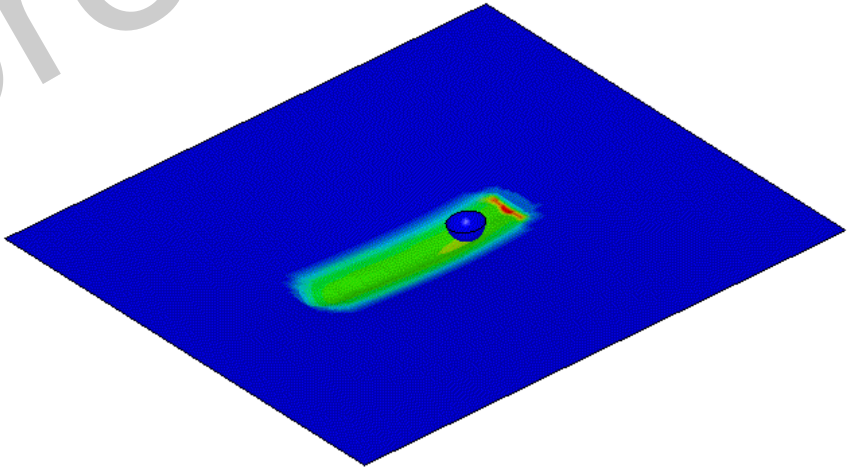
- Application for welding or laser assisted forming processes

*BOUNDARY_FLUX_SET

- Laser assisted sheet forming:
  - the laser heats the material and softens it for forming
  - Energy from the laser is modeled using a flux boundary condition



Deformation



Temperature

Welding simulations – requirements

- Realistic description for the heat source applied to the weld seam

- Weld seams are usually discretised with solid elements in the pre-processing
  - Before the weld torch has reached the material, filler should not influence the outcome
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  - The Goldak heat source
  - Heat sources with arbitrary shape and prescribed trajectories

- Suitable Material formulations in LS-DYNA
  - *MAT_CWM (*MAT_270)
  - *MAT_THERMAL_CWM (*MAT_T07)
  - *MAT_UHS_STEEL (*MAT_244)

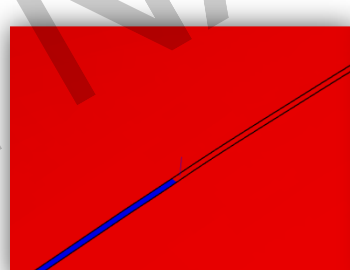
- Summary and Outlook

*MAT_CWM / *MAT_270

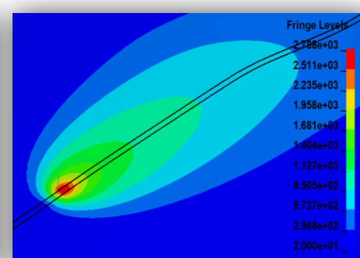
- Elements are initialy ”Ghost” or ”Silent” until activated at a specific temp.
  - Low stiffness
  - Negligible thermal expansion

- After activation, material with
  - Temperature dependent mechanical properties
  - Von-Mises plasticity with mixed isotropic/kinematic hardening
  - Thermal expansion

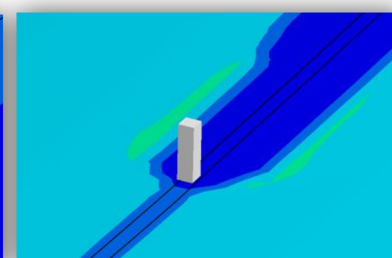
- Anneal at specific temperature



activation



temperatures



annealing

*MAT_CWM / *MAT_270

	1	2	3	4	5	6	7	8
Card 1	MID	RO	LCEM	LCPR	LCSY	LCHR	LCAT	BETA
Card 2	TASTART	TAEND	TLSTART	TLEND	EGHOST	PGHOST	AGHOST	
Opt.	T2PHASE	T1PHASE						

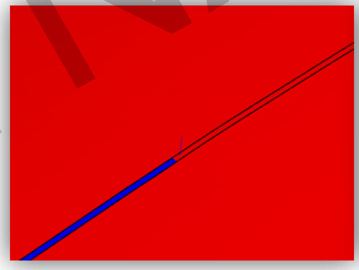
- Card1 contains properties for activated material
- TASTART and TAEND define range for annealing (linear process)
- TLSTART and TLEND define range for activation
- EGHOST, PGHOST and AGHOST are properties for ghost material
- T2PHASE and T1PHASE define temperature for phase shift

- Now available for shell and solid elements

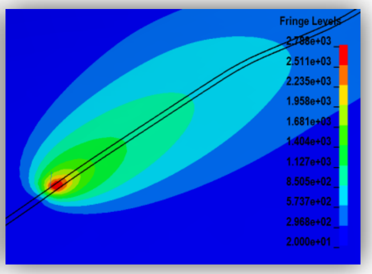
*MAT_THERMAL_CWM / *MAT_T07

	1	2	3	4	5	6	7	8
Card 1	TMID	TRO	TGRLC	TGRMULT	HDEAD	TDEAD		
Card 2	LCHC	LCTC	TLSTART	TLEND	TISTART	TIEND	HGHOST	TGHOST

- Material has birth time TISTART and TIEND
- Before birth, HDEAD and TDEAD are used
- After birth, material is in a “Ghost” state until activated between TLSTART and TLEND
- All input for activated material is temperature dependent
- TGR stands for thermal generation rate

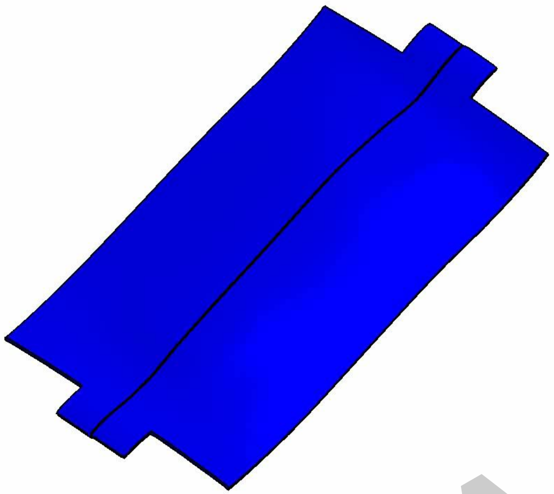


activation

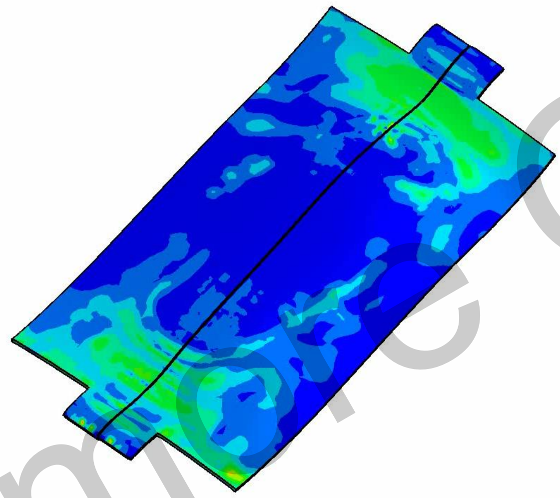


temperatures

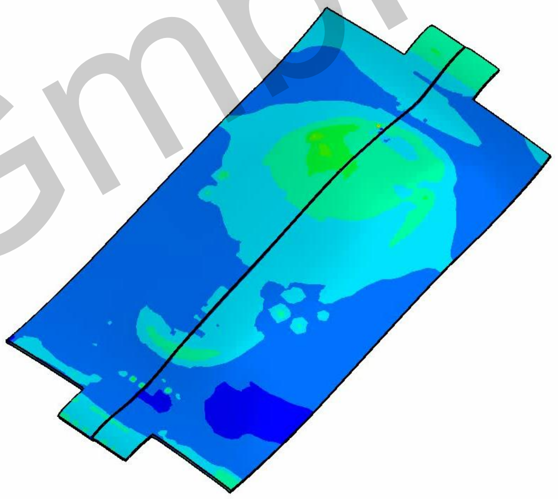
Welding simulation



Temperature



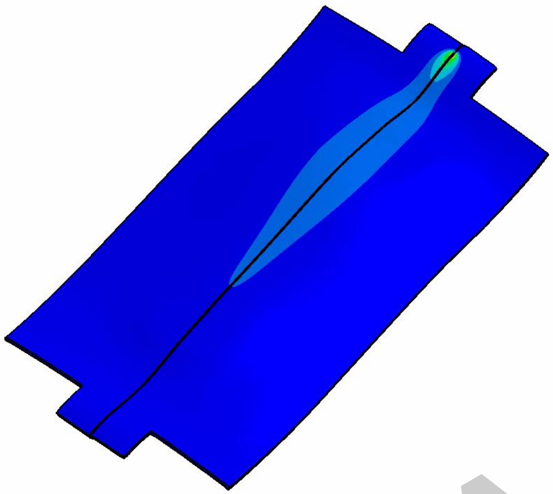
Von Mises stress



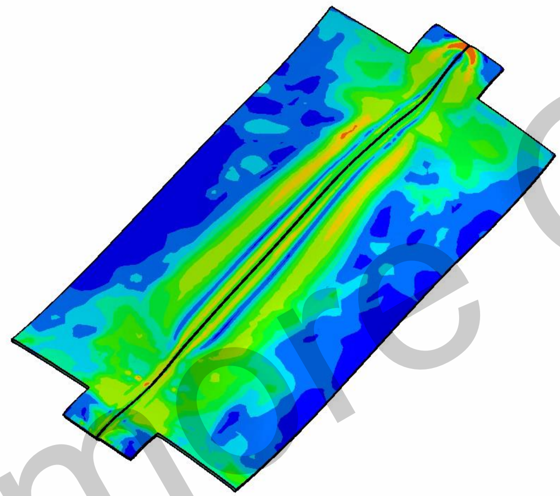
Effective plastic strain

After forming and trimming, but before welding

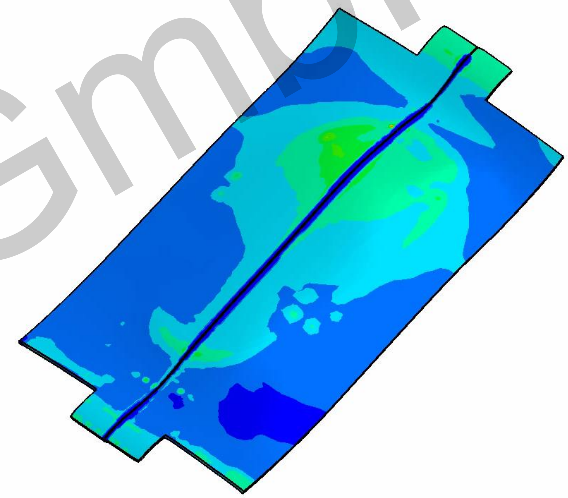
Welding simulation



Temperature



Von Mises stress



Effective plastic strain

After welding

Welding simulations – requirements

- Realistic description for the heat source applied to the weld seam ✓
- Weld seams are usually discretised with solid elements in the pre-processing
  - Before the weld torch has reached the material, filler should not influence the outcome
    - Very low mechanical stiffness
    - Very low heat conduction
  - If affected by the heat, material should respond as the surrounding material ✓
- Due to the very high temperature, annealing effects have to be considered ✓
- Material should be able to account for the microstructure of the alloy
  - Phase changes in heating and cooling
  - Transformation induced strains

*MAT_UHS_STEEL / *MAT_244

- The start temperatures for cooling phase transitions can be
  - calculated automatically by the material using the chemical composition
  - Defined manually using the advanced reaction kinetics input (`REACT`=1)

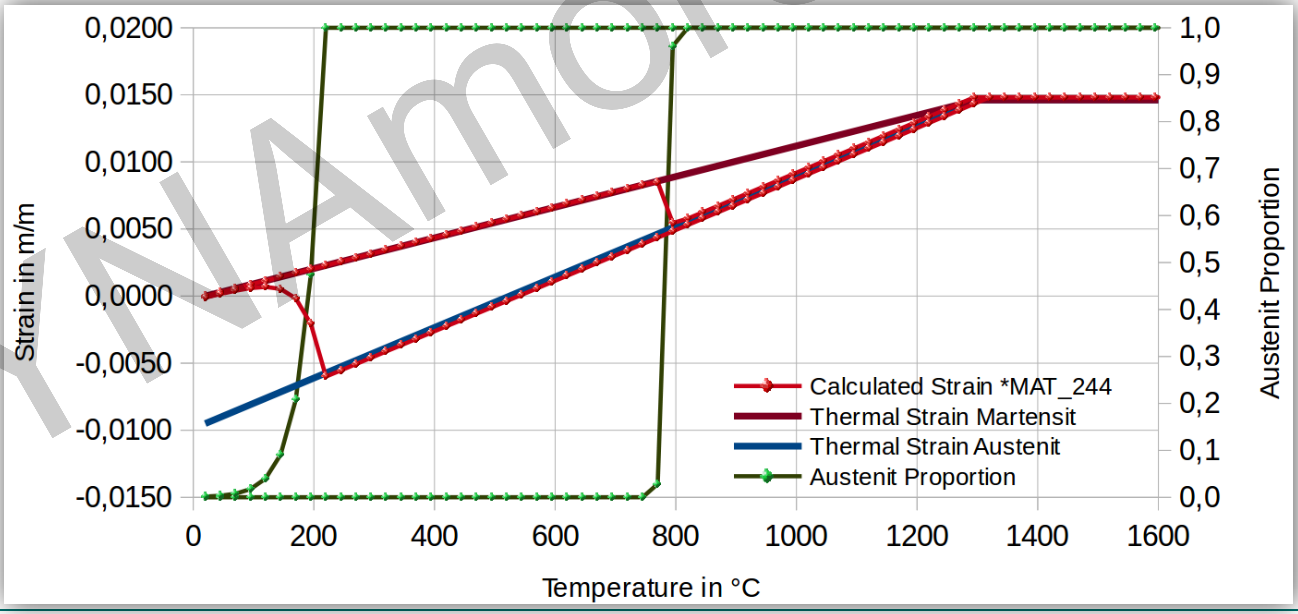
- By default, same start temperature is used for heating and cooling

	1	2	3	4	5	6	7	8
REACT	FS	PS	BS	MS	MSIG	LCEPS23	LCEPS4	LCEPS5

- Now, advanced reaction kinetics input accepts LCID for `FS,PS, BS, MS`
  - First ordinate value is start temperature for cooling
  - Last ordinate defines start temperature for heating

*MAT_UHS_STEEL / *MAT_244

- Temperature dependent definition for thermal expansion for austenite and the hard phases
- Dilatometer experiments show transformation induced strains as temperature dependent jumps
- Added parameter `LCTRE` in card 4 on position 8 defining temperature dependent offset between austenite and martensite dilatometer curve



LSTC Livermore Software Technology Corp.

DYNA MORE

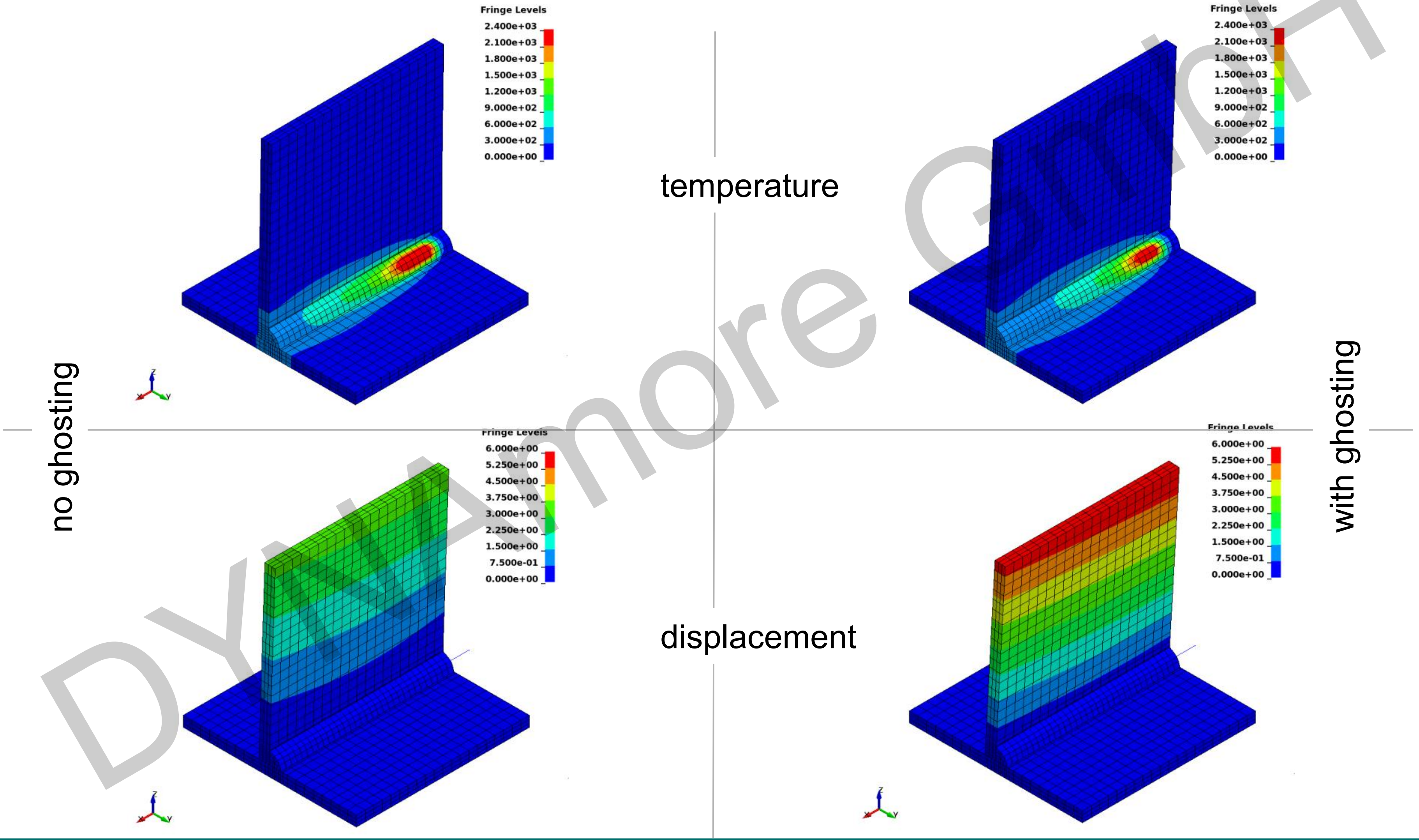
*MAT_UHS_STEEL / *MAT_244

- New features for welding have been implemented
- Can be used by setting flag `CWM` in card 4 parameter 7 to 1
- Optional CWM card reads

	1	2	3	4	5	6	7	8
CWM	TASTART	TAEND	TLSTART	TLEND	EGHOST	PGHOST	AGHOST	

- Ghost material approach as for *MAT_270
  - Material is inactive at the beginning, but is activated if temperature reaches the activation range from TLSTART to TLEND
  - Properties EGHOST, PGHOST and AGHOST of ghost material should not influence the outcome, but should yield suitable mesh movement within the weld seam
- Annealing is also considered
- Can be combined with *MAT_THERMAL_CWM

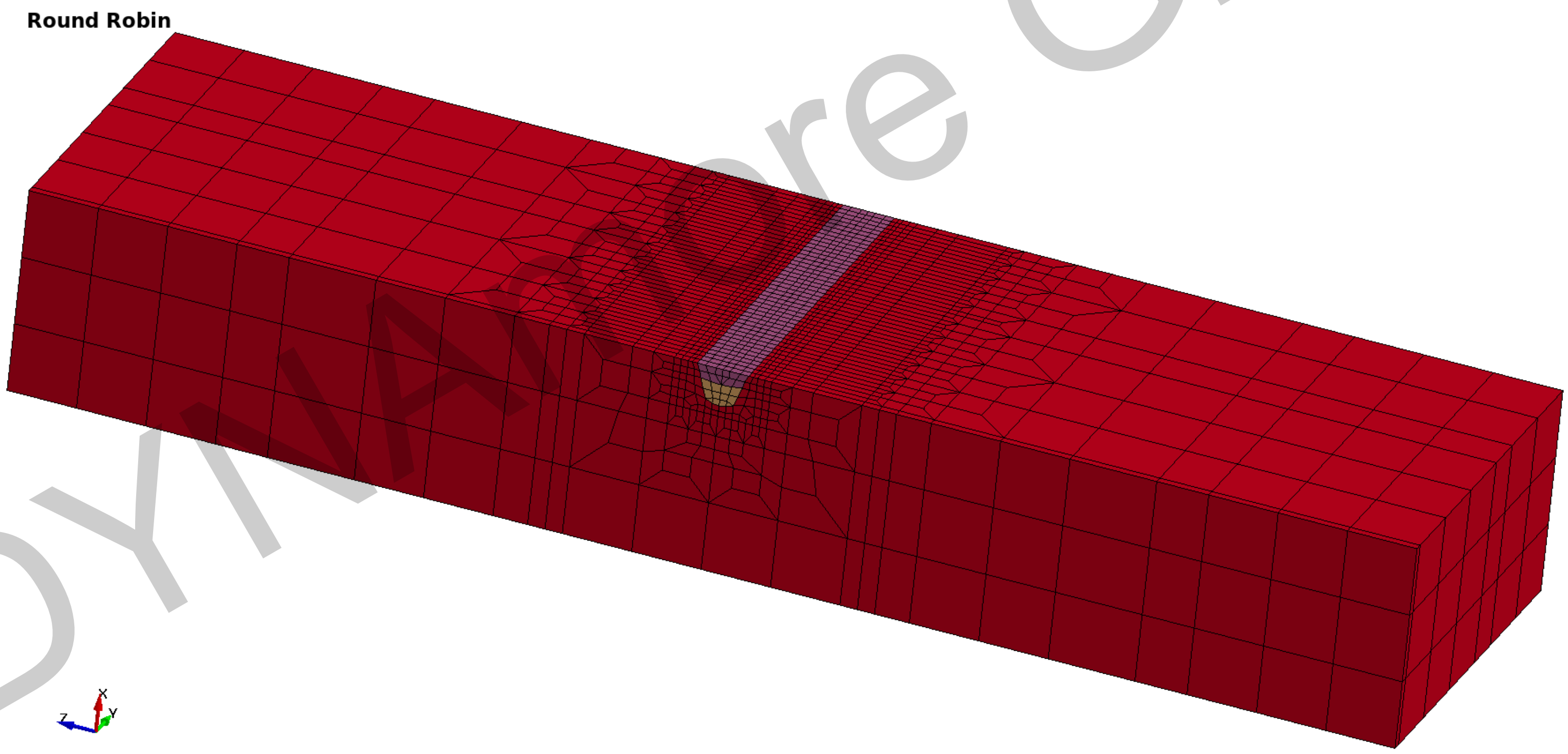
*MAT_UHS_STEEL / *MAT_244



*MAT_UHS_STEEL / *MAT_244

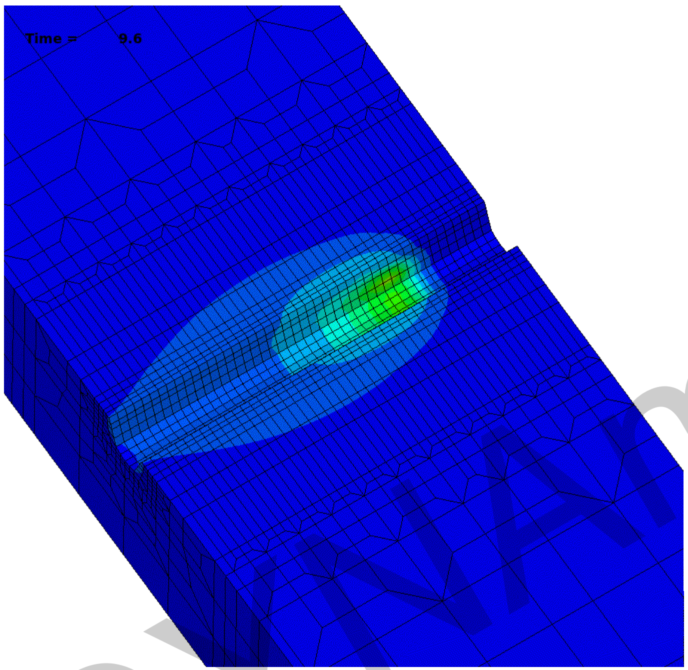
Example: Round Robin

- Geometry: notched block with 2 weld seams
- All materials are initialized in ferrite phase

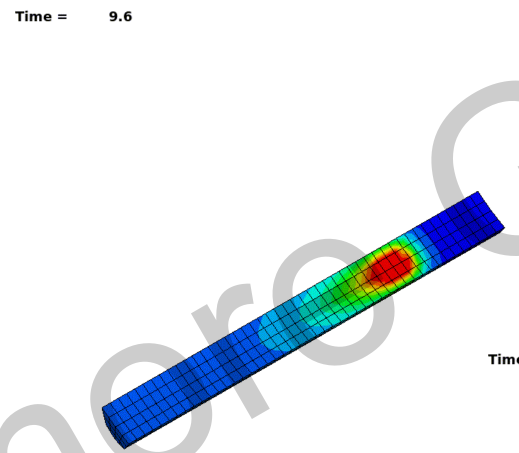


*MAT_UHS_STEEL / *MAT_244

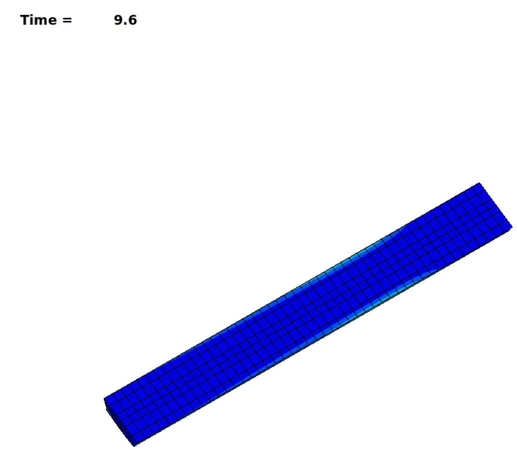
- **Temperature t=28**



block



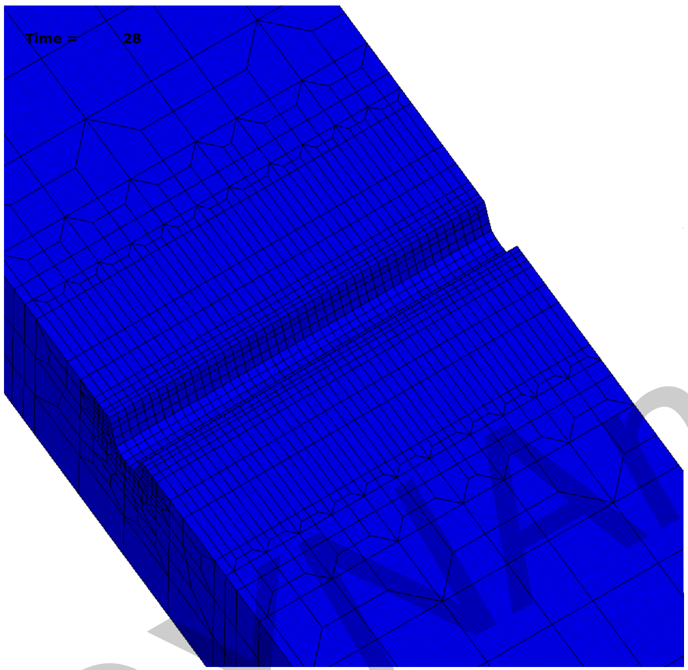
lower weld seam



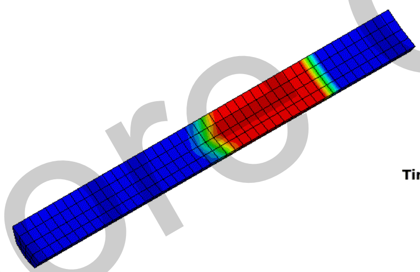
upper weld seam

*MAT_UHS_STEEL / *MAT_244

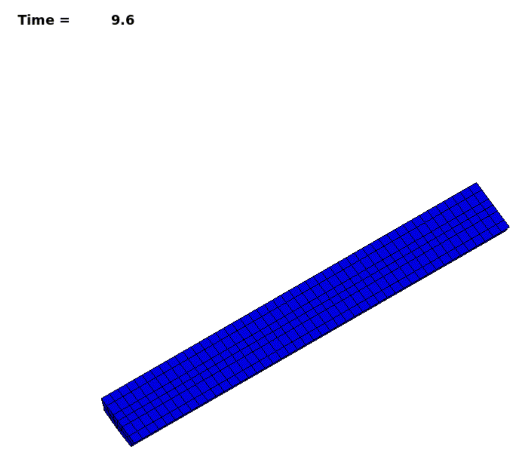
- **Austenite concentration t=28**



block



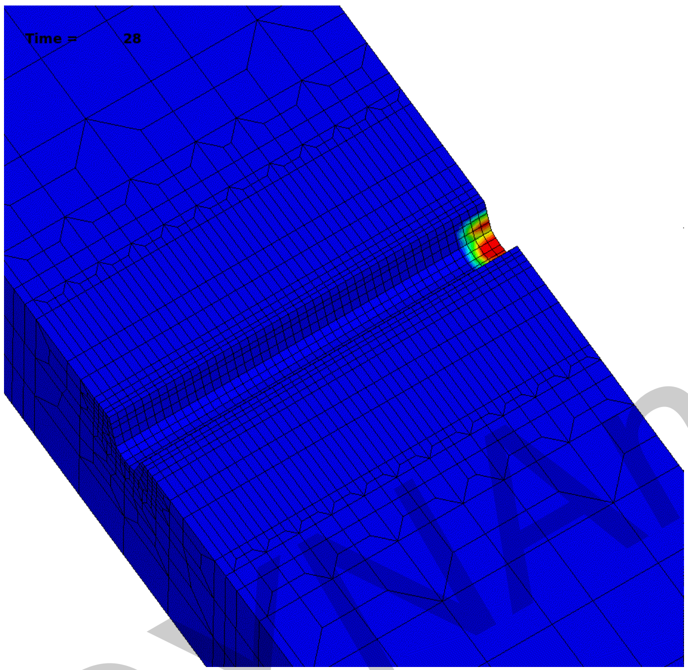
lower weld seam



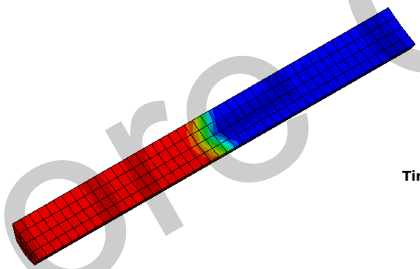
upper weld seam

*MAT_UHS_STEEL / *MAT_244

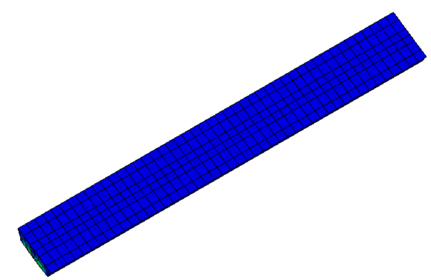
- **Martensite concentration t=28**



block



lower weld seam



upper weld seam

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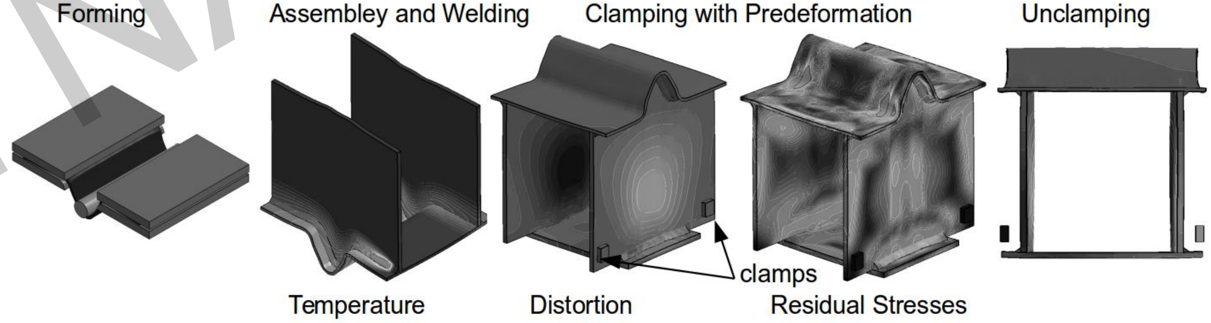
Summary

- Realistic description for the heat source applied to the weld seam
- Weld seams are usually discretised with solid elements in the pre-processing
  - Before the weld torch has reached the material, filler should not influence the outcome
    - Very low mechanical stiffness
    - Very low heat conduction
  - If affected by the heat, material should respond as the surrounding material
- Due to the very high temperature, annealing effects have to be considered
- Material should be able to account for the microstructure of the alloy
  - Phase changes in heating and cooling
  - Transformation induced strains

Outlook

- A generalization of *MAT_244 will be implemented
  - Suitable for a wider range of materials
  - More phases can be defined
  - Multiple phase transformations

- Special welding contact in currently under development at LSTC
  - Standard sliding contact at the beginning
  - Contact switches to a tied formulation after the weld temperature is reached



Thank you!